Linking Deconfinement and Chiral Symmetry Restoration

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Phase Transition(s) in QCD

deconfinement $SU(N_c)$ Yang-Mills: Z_{N_c} symmetry

order parameter: Polyakov loop ℓ , $\ell \to z\ell$ with $z \in Z_{N_c}$

$$\langle \ell \rangle = 0 \quad T < T_d \qquad\qquad \langle \ell \rangle \neq 0 \quad T > T_d$$

$\langle \ell \rangle \sim e^{-\frac{F_q}{T}}$, F_q free energy of $m_q \to \infty$

$N_\mathrm{c} = 2$ second order, $N_\mathrm{c} = 3$ weakly first order

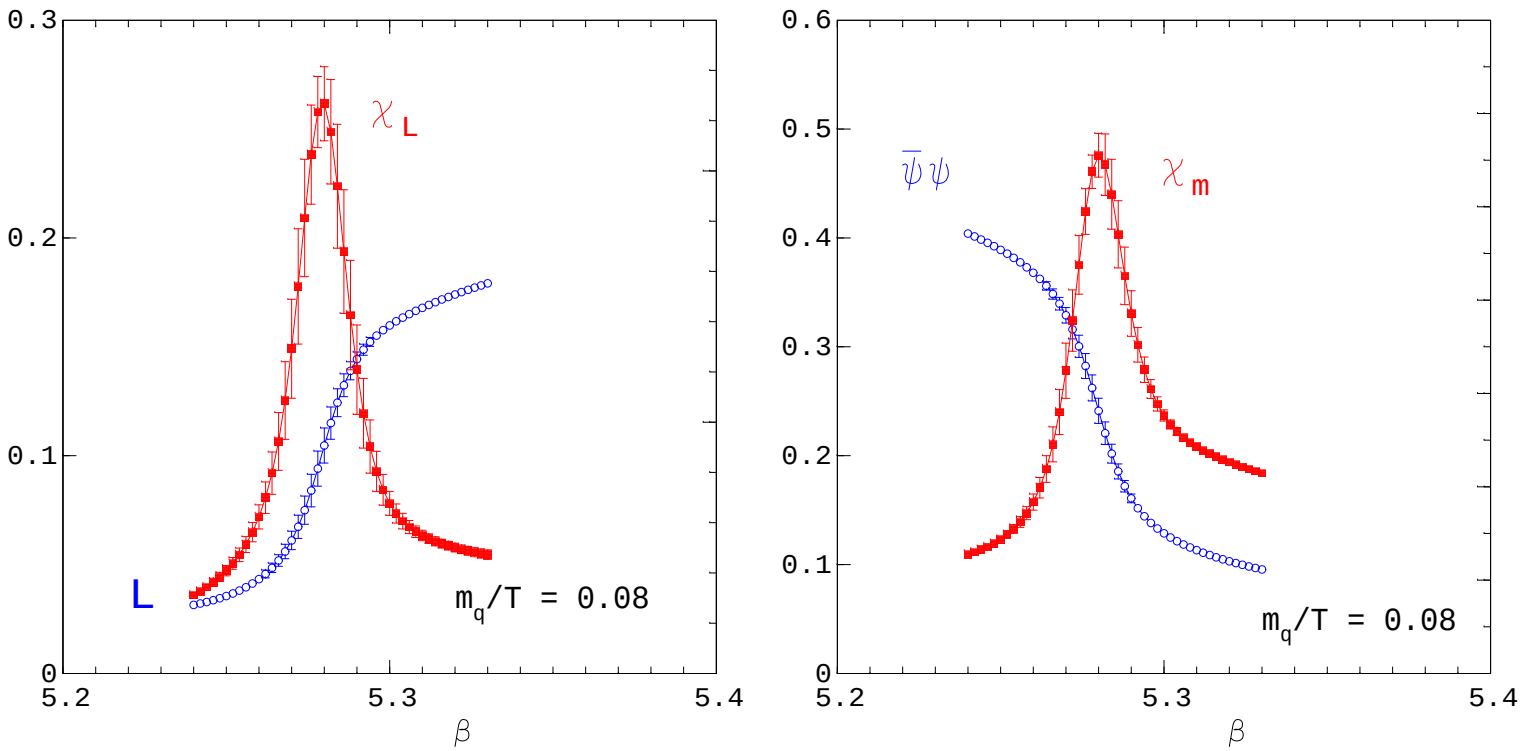
chiral symmetry restoration QCD with $m_q = 0$: chiral symmetry

order parameter: chiral condensate $\bar{\psi}\psi$

$$\langle \bar{\psi}\psi \rangle \neq 0 \quad T < T_{ch} \qquad\qquad \langle \bar{\psi}\psi \rangle = 0 \quad T > T_{ch}$$

$N_c = 2, 3$ and $N_f = 2$ second order

m_q finite – no true order parameter



F.Karsch, Lect.Notes Phys. (2002)

$T_{ch} = T_d$

EVIDENCE FOR A SINGLE QCD PHASE TRANSITION

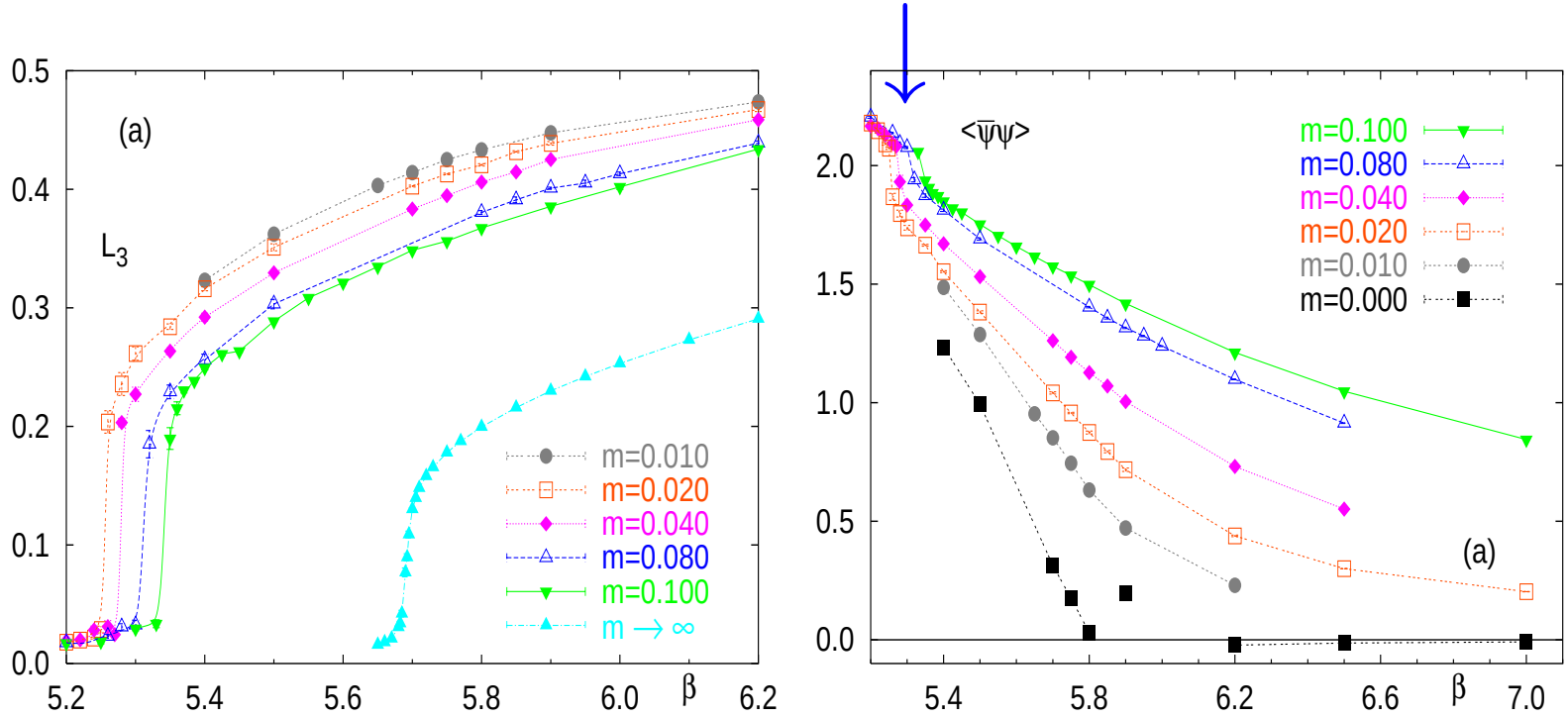
WHY?

QCD-like Theories

adjoint QCD

Z_{N_c} and chiral symmetry – order parameters: $\langle \ell \rangle$ and $\langle \bar{\psi}\psi \rangle$

– the two transitions can be studied independently –



$T_{ch} \simeq 8T_d$

F.Karsch, M.Lütgemeier, NPB (1999)

WHY?

The General Theory

◇ order parameter field (o.p) – knows the symmetry

◇ non-order parameter field (n.o.p) – scalar singlet

◇ near T_c

$$m_{o.p} \ll T \ll m_{n.o.p} \qquad\qquad m_{o.p}(T) \sim |T - T_c|^{\nu}$$

$\langle$o.p field$\rangle \neq 0$ in symmetry broken phase <u>induces</u> variation in $\langle$n.o.p field$\rangle$

spatial correlators of n.o.p fields dominated at T_c by the critical behavior of o.p

finite drop in the screening mass of any scalar singlet field at T_c

F.Sannino, PRD (2002)
A.M., F.Sannino, K.Tuominen, PRL (2003); hep-ph/0306069

Quarks in Fundamental Representation $N_c = N_f = 2$

order parameter: chiral σ field

$$V_{\rm ch}[\sigma, \pi^a] = \frac{m^2}{2}{\rm Tr}\left[M^\dagger M\right] + \lambda_1 {\rm Tr}\left[M^\dagger M\right]^2 + \frac{\lambda_2}{4}{\rm Tr}\left[M^\dagger M M^\dagger M\right]$$

$$V_\chi[\chi] = g_0\chi + \frac{m_\chi^2}{2}\chi^2 + \frac{g_3}{3}\chi^3 + \frac{g_4}{4}\chi^4\,, \qquad \chi \text{ is Polyakov loop}$$

$$V_{\rm int}[\chi, \sigma, \pi^a] = \left(g_1\chi + g_2\chi^2\right)\left(\sigma^2 + \pi^a\pi^a\right)$$

EXPECTATION VALUES

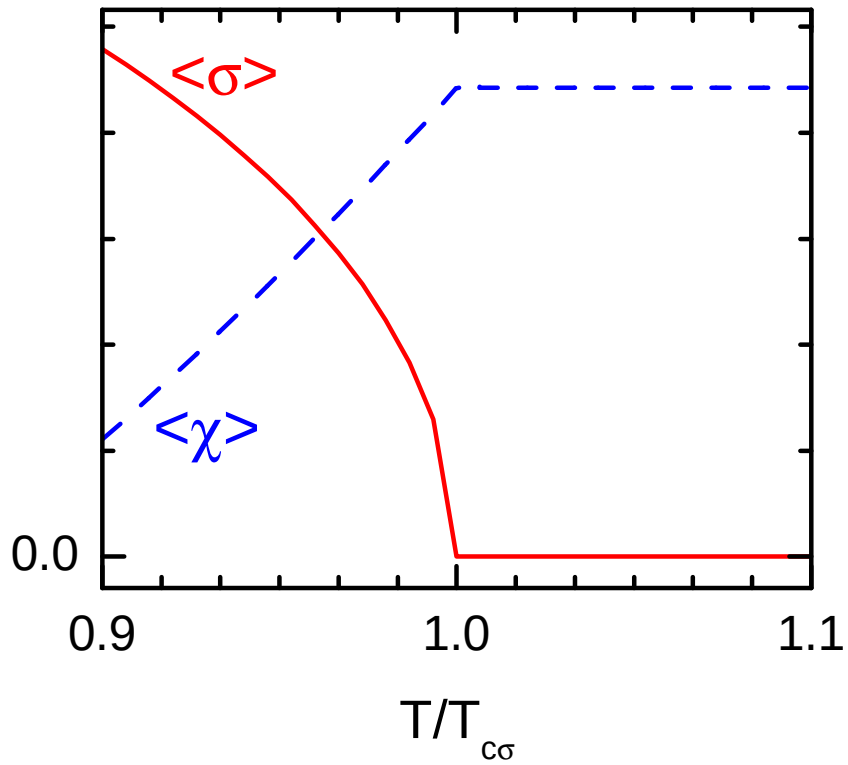
broken phase $T < T_{c\sigma}$

$$\langle\sigma\rangle^2 \simeq -\frac{m_\sigma^2}{\lambda}$$

$$m_\sigma^2 \simeq m^2 + 2g_1\langle\chi\rangle < 0$$

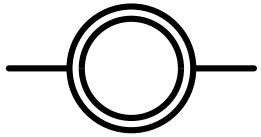
$$\langle\chi\rangle \simeq -\frac{g_0}{m_\chi^2} - \frac{g_1}{m_\chi^2}\langle\sigma\rangle^2$$

$$g_1 > 0\ ,\ g_0 < 0$$



chiral symmetry restoration induces deconfinement

SPATIAL CORRELATOR OF N.O.P FIELD

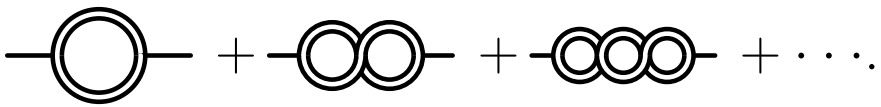


$$\sim g_1^2 \int \frac{d^3k}{(2\pi)^3} \frac{1}{(k^2 + m_{o.p}^2)^2} \sim \frac{g_1^2}{m_{o.p}}$$

screening mass

$$\Delta m_{n.o.p}(T) = m_{n.o.p}^2(T) - m_{n.o.p}^2 \sim -\frac{g_1^2}{|m_{o.p}|} \sim t^{-\frac{\nu}{2}}$$

IR singularity at $T = T_c$



Exact in $O(N)$ for large N

spatial two-point correlator of Polyakov loop

$$\text{drop in screening mass} = -\frac{2g_1^2(1+N_\pi)}{8\pi\, m_\sigma + (1+N_\pi)3\lambda} \qquad T \geq T_{c\sigma}$$

$$\text{drop in string tension} = -\frac{2g_1^2}{8\pi\, M_\sigma + 3\lambda} \qquad T \leq T_{c\sigma}$$

Quarks in Adjoint Representation $N_c = N_f = 2$

order parameters: chiral σ field and Polyakov loop χ

$$V_{\rm ch}[\sigma, \pi^a] = \frac{m^2}{2}{\rm Tr}\left[M^\dagger M\right] + \lambda_1 {\rm Tr}\left[M^\dagger M\right]^2 + \frac{\lambda_2}{4}{\rm Tr}\left[M^\dagger M M^\dagger M\right]$$

$$V_\chi[\chi] = \frac{m_{0\chi}^2}{2}\chi^2 + \frac{g_4}{4}\chi^4$$

$$V_{\rm int}[\chi, \sigma, \pi] = g_2 \chi^2 (\sigma^2 + \pi^a \pi^a)$$ no $\chi\sigma^2$ term

$T_{c\sigma} \ll T_{c\chi}$

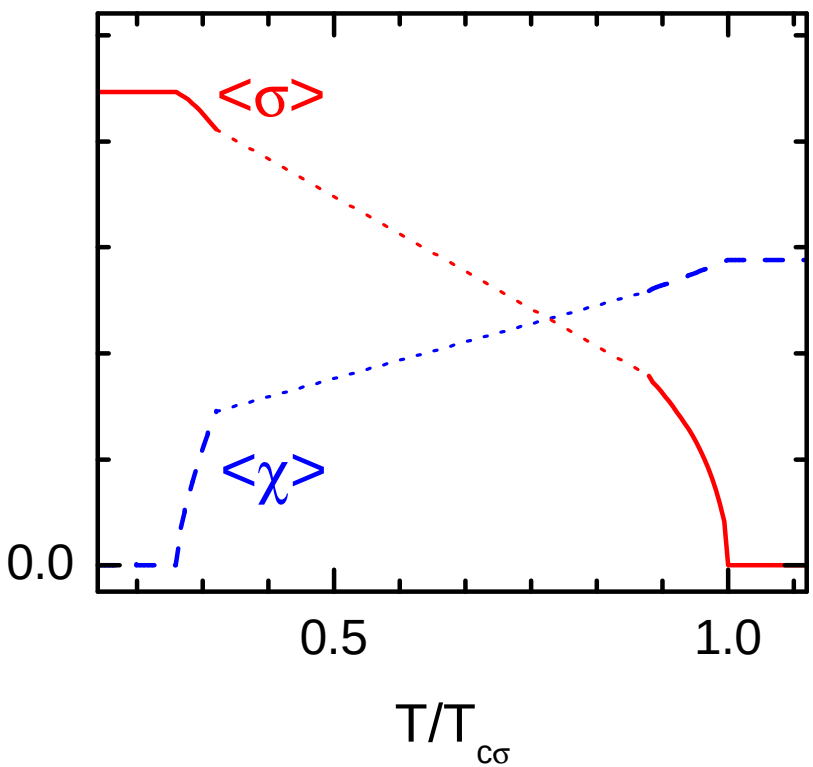
$T < T_{c\sigma}$: $\langle\sigma\rangle\sigma\chi^2$ and $T > T_{c\chi}$: $\langle\chi\rangle\chi\sigma^2$ exists, but harmless

fully separated transitions & neither of the fields feels the transition of the other

$T_{c\chi} \ll T_{c\sigma}$

$T_{c\chi} < T < T_{c\sigma}$

$$\langle\sigma\rangle^2 = -\frac{1}{\lambda}\left(m^2 + 2g_2\langle\chi\rangle^2\right) \equiv -\frac{m_\sigma^2}{\lambda} \qquad \langle\chi\rangle^2 = -\frac{1}{g_4}\left(m_{0\chi}^2 + 2g_2\langle\sigma\rangle^2\right) \equiv -\frac{m_\chi^2}{g_4}$$



near $T_{c\chi}$: $\langle\sigma\rangle\sigma\chi^2$; $\Delta m_\sigma^2(T_{c\chi}) \sim -\langle\sigma\rangle^2$
near $T_{c\sigma}$: $\langle\chi\rangle\chi\sigma^2$; $\Delta m_\chi^2(T_{c\sigma}) \sim -\langle\chi\rangle^2$

the two fields do feel each other near the respective phase transitions

existence of substructures near T_c's

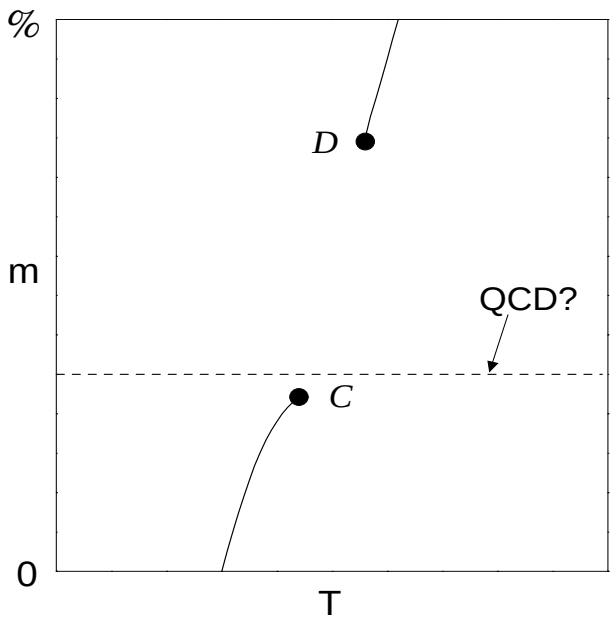
Conclusions and Further Thoughts

◇ info encoded in o.p efficiently communicated to n.o.p via trilinear coupling

◇ massless (light) quarks in the fundamental:
– confinement (rise in PL) is driven by the chiral transition –

◇ very heavy quarks:
– deconfinement drives the (approximate) restoration of chiral symmetry –

◇ aQCD – existence of substructures

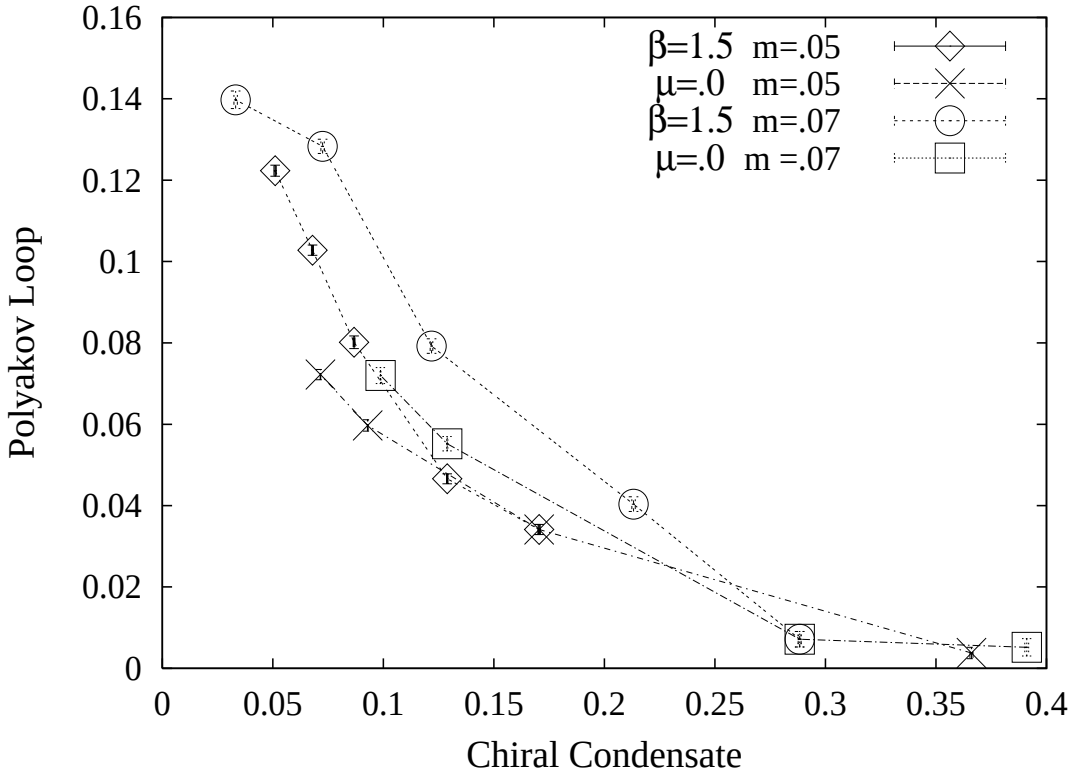


To what extent is the QCD phase transition deconfining or chiral symmetry restoring?

S.Gavin, A.Gocksch, R.D.Pisarski, PRD (1994)
A.Dumitru, D.Röder, J.Ruppert, hep-ph/0311119

◇ 2QCD at $\mu \neq 0$

transition from quark-antiquark condensate to diquark condensate



$\mu_{ch} = \mu_d$

B. Alles, M.D'Elia, M.P.Lombardo, M.Pepe, hep-lat/0210039